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Distribution and habitat suitability of two neighboring Lycian salamanders

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***Abstract.—Lyciasalamandra fazilae* and *Lyciasalamandra flavimembris* are two Endangered and endemic species which occur only in Muğla province of Turkey. In protecting an endemic or endangered species, the first step is to understand its potential and/or known distribution. Therefore, we used the Maximum Entropy modelling software (MaxEnt) to analyze the current potential distribution and most important habitat features associated with the localities of these two species. The variables with the highest contributions to the model were: Bedrock, Precipitation of Coldest Quarter, and Normalized Difference Vegetation Index for *L. flavimembris*; and Bedrock, Temperature Seasonality, Precipitation Seasonality, and Precipitation of Coldest Quarter for *L. fazilae*. We also identified two new localities for *L. flavimembris* using the habitat suitability model.**

Keywords. Climate, conservation, Endangered, endemic, habitat suitability map, new localities

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Introduction

There are only seven species of Lycian salamanders in the world, six of which are found in Turkey. Among them, the Marmaris Salamander [*Lyciasalamandra flavimembris* (Mutz and Steinfertz 1995)] and the Göcek Salamander [*Lyciasalamandra fazilae* (Başoğlu and Atatür, 1974)] are local endemic species distributed in the Muğla province of Turkey. *Lyciasalamandra fazilae* occurs in the eastern part of Muğla province (Fethiye, Göcek, Ortaca, and Köyceğiz districts), while *L. flavimembris* occurs in the western part of Muğla province (Milas, Ula, and Marmaris districts). Both species were formerly considered to be subspecies of *Mertensiella luschani*, with *L. flavimembris* even being con-subspecific with *L. helverseni* from the Greek Karpathos archipelago. However, previous studies have shown that they are morphologically and phylogenetically separate species (Öz et al. 2004; Veith et al. 2016, 2020; Veith and Steinfartz 2004), and their colorations are clearly distinguishable (Öz et al. 2004; Özeti and Yılmaz 1994).

Amphibians are highly susceptible to any changes in their habitat because of their highly permeable skin, and many species spend their lives in both terrestrial and freshwater habitats (Alford and Richards 1999; Barinaga 1990; Duellman and Trueb 1994). The current information on the ecology of Lycian salamanders broadly covers all species in this genus, and is therefore considered to be generally applicable to all of them (cf. Özeti and Yılmaz 1994). On this basis, the *Lyciasalamandra* species are terrestrial, inhabiting rocky limestone areas mostly in pine forests and maquis—sometimes near single-standing pines and olive trees, sometimes in deciduous forests dominated by oaks and junipers, and occasionally in accumulations of rocks or on slopes without vegetation (e.g., Baran and Atatur 1998; Başoğlu and Özeti 1973; Veith et al. 2001). The vertical distributions of these species are known to range from 25 to 1,400 m asl, where the mean annual rainfall may be less than 1,000 mm (Veith et al. 2001; Yıldız and Akman 2015).

Lyciasalamandra fazilae and *L. flavimembris* are listed as Endangered by the IUCN Red List of Threatened Species (http://www.iucnredlist.org; Accessed: 4 May 2020) in view of their naturally restricted ranges and the continuing decline of their habitats. In protecting an endemic and/or Endangered species, the first step is to understand its potential and/or known distribution (Sousa-Silva et al. 2014). Intense research on the existing distribution of Lycian salamanders is time-consuming and expensive, but modelling their distributions could provide more accurate results with less time and effort (Hernandez et al. 2006). Species Distribution Modelling

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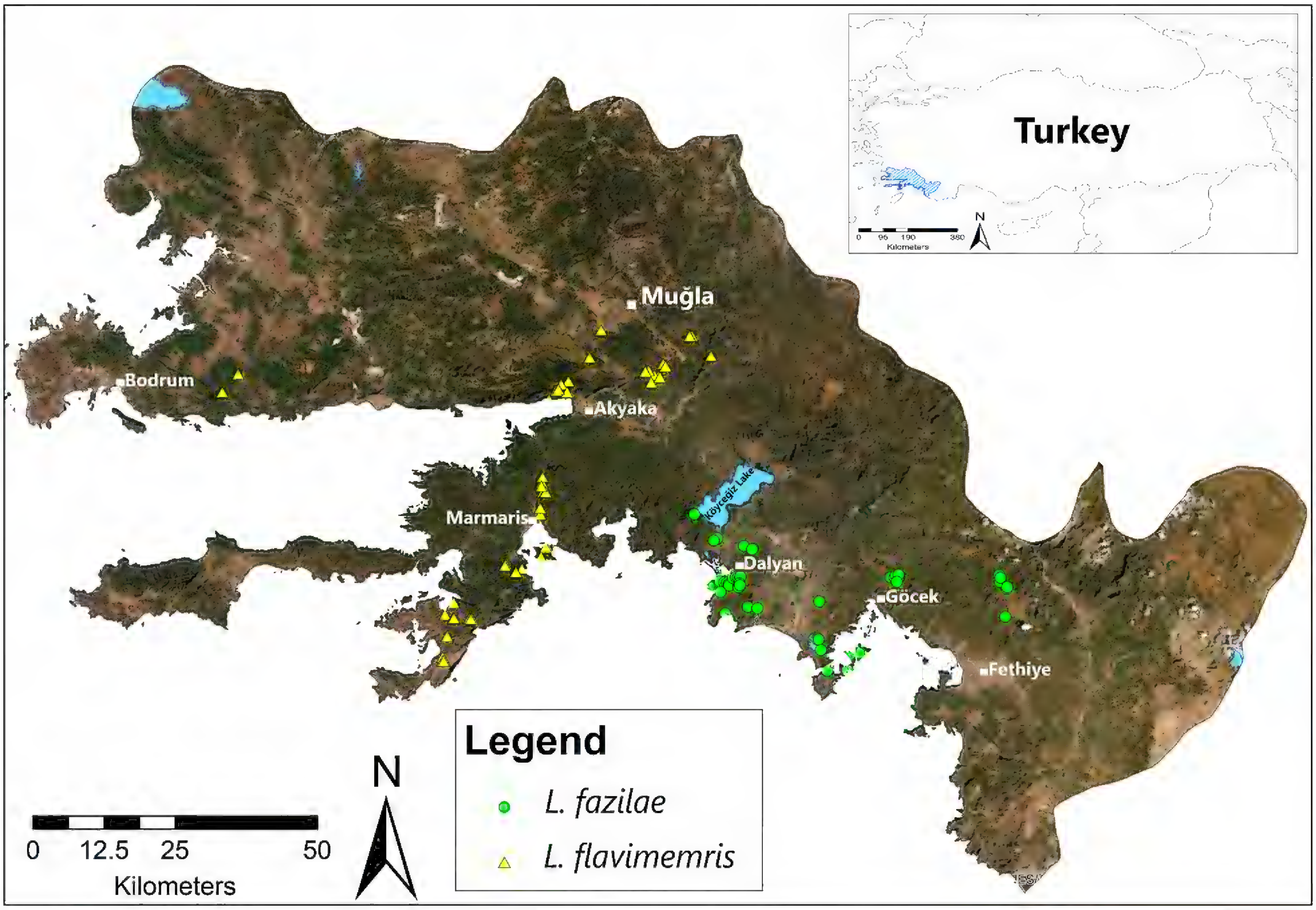


Fig. 1. Study area and distributions of presence data for *L. flavimembris* and *L. fazilae*.

(SDM) is a correlative approach in which habitat suitability, and therefore the distribution of a species, is estimated on the basis to environmental and geographical information (Elith and Graham 2009). The resulting models are called habitat suitability models, and they are considered to be important for the conservation of a species' habitat and the implementation of conservation action plans (Buckland and Elston 1993; Marzluff et al. 2002). They can be used to identify potential risks to a species and thus to prioritize habitat conservation, to optimize land management planning, and to allocate suitable habitats for potential translocation programs (Corsi et al. 1999; Özkan and Berger 2014; Stoms et al. 1992).

The effective conservation of amphibian populations is typically limited by the lack of species-specific ecological knowledge. Therefore, this study was conducted to identify the environmental variables which limit the distribution of Marmaris Salamander and Göcek Salamander, and to determine their current and potential habitats. We believe that the models and maps obtained through the MaxEnt method will provide a base for the successful execution of species protection action plans.

Materials and Methods

Species data and study area. Between 2012 and 2020, field studies were carried out during the activity period of the salamanders (October–April) within the province of Muğla, Turkey (Fig. 1). The study sites included four Specially Protected Areas (Gökova SPA, Datça-Bozburun SPA, Fethiye-Göcek SPA, and Köyceğiz Dalyan SPA), one National Park (Marmaris NP), and a Wildlife Development Area (Köyceğiz). The elevations of the sites ranged from 0 to 1,300 m asl. The climate is dominated by the Mediterranean climate. Urbanized areas, touristic areas, and natural areas without human intervention constitute important places in the study area which are mostly covered with maquis areas (shrublands), Red Pine (*Pinus brutia*) dominated coniferous forest, and agricultural fields. The field studies were carried out during both day and night. A total of 240 sample areas were examined, each with a size of 874 m × 874 m (i.e., the resolution of the Worldclim [version 2.1] data used as described below). The altitudes and coordinates of each salamanders' presence point were recorded with a Garmin 62S GPS receiver using the WGS 84 coordinate system.

Environmental data. The Aster Global Digital Elevation Model (GDEM), version 3, was obtained from Earthdata (http://earthdata.nasa.gov). Altitude, aspect, and slope were produced using GDEM (Zeiler 1999) in ArcMap 10.2 software. The Topographic Position Index (TPI), Topographic Wetness Index (TWI), Landform Position Index (LPI), roughness index, hillshade index, ruggedness index, solar radiation index, and solar illumination index (at 0600 h, 0800 h, 1000 h, 1200 h, 1400 h, 1600 h, 1800 h, 2000 h, and total solar illumination) were created with the help of the "Topography tools" plugin included in ArcGIS 10.2 (Jenness 2006). The NDVI (Normalized Difference Vegetation Index) data produced by the MOD13Q1 module, which is one of the MODIS VI satellite data sources, was cut and used at the study area scale. NDVI values range from -1 to +1. Negative values represent water, snow, clouds, and non-plant areas; while positive values indicate the presence of vegetation. However, since negative values complicate the statistical analysis, the NDVI values were converted to the 0–10,000 range by using the formula: NDVI * 10,000 (Çelik and Gülersoy 2017). The bedrock map of the study area was obtained from the General Directorate of Mineral Research and Exploration (Maden Tetkik ve Arama Genel Müdürlüğü, http://yerbilimleri.mta.gov.tr/anasayfa.aspx). Different bedrock types (154) are shown in the form of polygons on the digital bedrock map obtained, which was used as a base map. These data were used as categorical data. Bioclimatic data representing the current climatic conditions of the study area were obtained from http://www.worldclim.org (Fick and Hijmans 2017). These data (Worldclim, Version 2.1) were obtained in the WGS 84 coordinate system with the highest resolution (30 arc-seconds, or 874 m × 874 m), and in the ESRI Grid format. Nineteen bioclimatic variables (Bio1–Bio19, Table 1) with this feature were cut on the scale of the study area with the help of ArcMap 10.2. Temperature data (Bio1, Bio2, Bio5–Bio11) values are shown multiplied by 100.

For all of the digital base maps of the environmental variables in ASCII format, each cell was produced in the WGS 84 coordinate system (874 m × 874 m), and thus is of the same size as the sample areas.

Statistical evaluation, habitat suitability model, and habitat suitability model map. Due to the small size of the study area, high correlation is expected between the bioclimatic data and other environmental variables. This may pose a problem during the analysis. To eliminate the multicollinearity problem, we applied Pearson Correlation Analysis, using a threshold of $r^2 < 0.8$, for a total of 40 environmental variables. If a pair of variables was found to have a correlation coefficient greater than 0.8, they were considered to represent related phenomena, and one of them was excluded from the analysis.

Maximum Entropy (MaxEnt) (Phillips et al. 2006) is a popular habitat suitability modelling method, which provides more accurate results with less data in smaller areas compared with other methods (e.g., DOMAIN, BIOCLIM, and GARP) (Hernandez et al. 2006; Phillips and Dudík 2008; Wisz et al. 2008). In addition, MaxEnt enables the joint processing of categorical and continuous data (Phillips and Dudík 2008), and it produces a habitat suitability map (Elith et al. 2011; Hernandez et al. 2006, 2008). MaxEnt is based on ENFA (Ecological Niche Factor Analysis; Hirzel et al. 2002) and examines the characteristics of the locations of the target species, and then estimates a suitability level for all areas based on the values taken by the factors which affect the known distribution of the species (Baldwin 2009). In this respect, the MaxEnt method was used to evaluate the potential distributions of Marmaris Salamander and Göcek Salamander using MaxEnt 3.4.1 software (Phillips et al. 2006). MaxEnt calculates the maximum entropy to find the most likely geographical and ecological distribution of a target species. MaxEnt also examines the relationships between the asset data of the target species and environmental variables, and determines the ecological requirements of the target species. It then predicts the areas in which the target species will be more or less likely to appear based on the ecological requirements of the target species (Baldwin 2009).

The environmental data, including presence data, in CSV format and environmental variables in ASCII format were analyzed with the help of MaxEnt 3.4.1 software. Species data were separated into 90% for training data and 10% for test data using the software settings, and the analysis was adjusted to carry out ten repetitions. The replicated run type Crossvalidate was selected. Further settings were: maximum iterations = 500, convergence threshold = 0.00001, and default prevalence = 0.5. The Area Under the Receiver Operating Characteristic (ROC) Curves (AUC) was used to evaluate model performance. Finally, among the models with excellent model performance, the model with the lowest standard deviation between the training data AUC value and the test data AUC value was selected as "the best model," and the species distribution maps of that model were visualized with ArcMap 10.2 software.

Results

For *L. flavimembris* and *L. fazilae*, 83 and 66 presence data points were obtained from the field studies, respectively, of which 68 and 54 were used for the final models, respectively. Most of the presence data obtained during the field studies were either known localities or points very close to known localities (Arslan et al. 2018; Başkale et al. 2019; Göçmen et al. 2018; Oğuz et al. 2020; Polat and Başkale 2018; Veith et al. 2020). According to the results of the habitat suitability model, the training data set AUC value was 0.942 and the test data set AUC value was 0.941 ± 0.056 ($P < 0.001$) for *L. flavimembris* (Fig 2a); while for *L. fazilae* the training data set AUC value was 0.954 and the test data set AUC value was 0.948 ± 0.076 ($P < 0.001$) (Fig. 2b). These P values indicated that the model obtained was at the level of "perfect explanation" for the ecological requirements in the habitat preferences of both salamanders.

According to the percentages of their contributions to the MaxEnt model, the important or highly contributing

Table 1. Average contributions of the environmental variables according to MaxEnt, with the intervals of occurrence that explain the distributions of *L. flavimembris* and *L. fazilae*.

Variable	Reference	Units	*L. flavimembris*		*L. fazilae*	
			Contribution to the Model (%)	Interval of occurrence	Contribution to the Model (%)	Interval of occurrence
Bio1 (Annual Mean Temperature)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio2 (Mean Diurnal Range)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio3 (Isothermality)	Fick and Hijmans 2017	(Bio2/Bio7)*100	0	—	0	—
Bio4 (Temperature Seasonality)	Fick and Hijmans 2017	C of V	0	—	3.8	5–6 ºC
Bio5 (Max Temperature of Warmest Month)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio6 (Min Temperature of Coldest Month)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio7 (Temperature Annual Range)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio8 (Mean Temperature of Wettest Quarter)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio9 (Mean Temperature of Driest Quarter	Fick and Hijmans 2017	ºC	0	—	0	—
Bio10 (Mean Temperature of Warmest Quarter)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio11 (Mean Temperature of Coldest Quarter)	Fick and Hijmans 2017	ºC	0	—	0	—
Bio12 (Annual Precipitation)	Fick and Hijmans 2017	mm	0	—	0	—
Bio13 (Precipitation of Wettest Month)	Fick and Hijmans 2017	mm	0	—	0	—
Bio14 (Precipitation of Driest Month)	Fick and Hijmans 2017	mm	0	—	0	—
Bio15 (Precipitation Seasonality)	Fick and Hijmans 2017	C of V	0	—	8.5	100 mm
Bio16 (Precipitation of Wettest Quarter)	Fick and Hijmans 2017	mm	0	—	0	—
Bio17 (Precipitation of Driest Quarter)	Fick and Hijmans 2017	mm	0	—	0	—
Bio18 (Precipitation of Warmest Quarter)	Fick and Hijmans 2017	mm	0		0	—
Bio19 (Precipitation of Coldest Quarter)	Fick and Hijmans 2017	mm	41.7	500–650 mm	22.5	600 mm
Altitude	Zeiler 1999	m	0	—	0	—
Slope	Zeiler 1999	%	0	—	0	—
Aspect	Zeiler 1999	—	0	—	0	—
Topographic position index (TPI)	Jenness 2006	—	0	—	0	—
Topographic wetness index (TWI)	Jenness 2006	—	0	—	0	—
Landform position index (LPI)	Jenness 2006	Categorical	0	—	0	—
Roughness index	Jenness 2006	—	0	—	0	—
Hillshade index	Jenness 2006	—	0	—	0	—
Ruggedness index	Jenness 2006	—	0	—	0	—
Solar radiation index	Jenness 2006	—	0	—	0	—
Solar illumination index (at 0600 h, 0800 h, 1000 h, 1200 h, 1400 h, 1600 h, 1800 h, 2000 h, and total solar illumination)	Jenness 2006	—	0	—	0	—
NDVI (Normalized Difference Vegetation Index)	Nasa 2000	—	4.1	10,000	0	—
Bedrock	MTA 2019	Categorical	54.2	Cherty Limestone, Limestone, Pebble Stone-Sandstone-Mudstone, Peridotite, Dolomite, Spilite-Basalt-Tuff, Breccias, Alluvion, Chert, Melange	62.3	Alluvion, Cherty Limestone, Dolomite, Limestone, Peridotite , Sandstone-Mudstone, Sandstone-Mudstone-Limestone, Volcanite-Sedimentary Rock

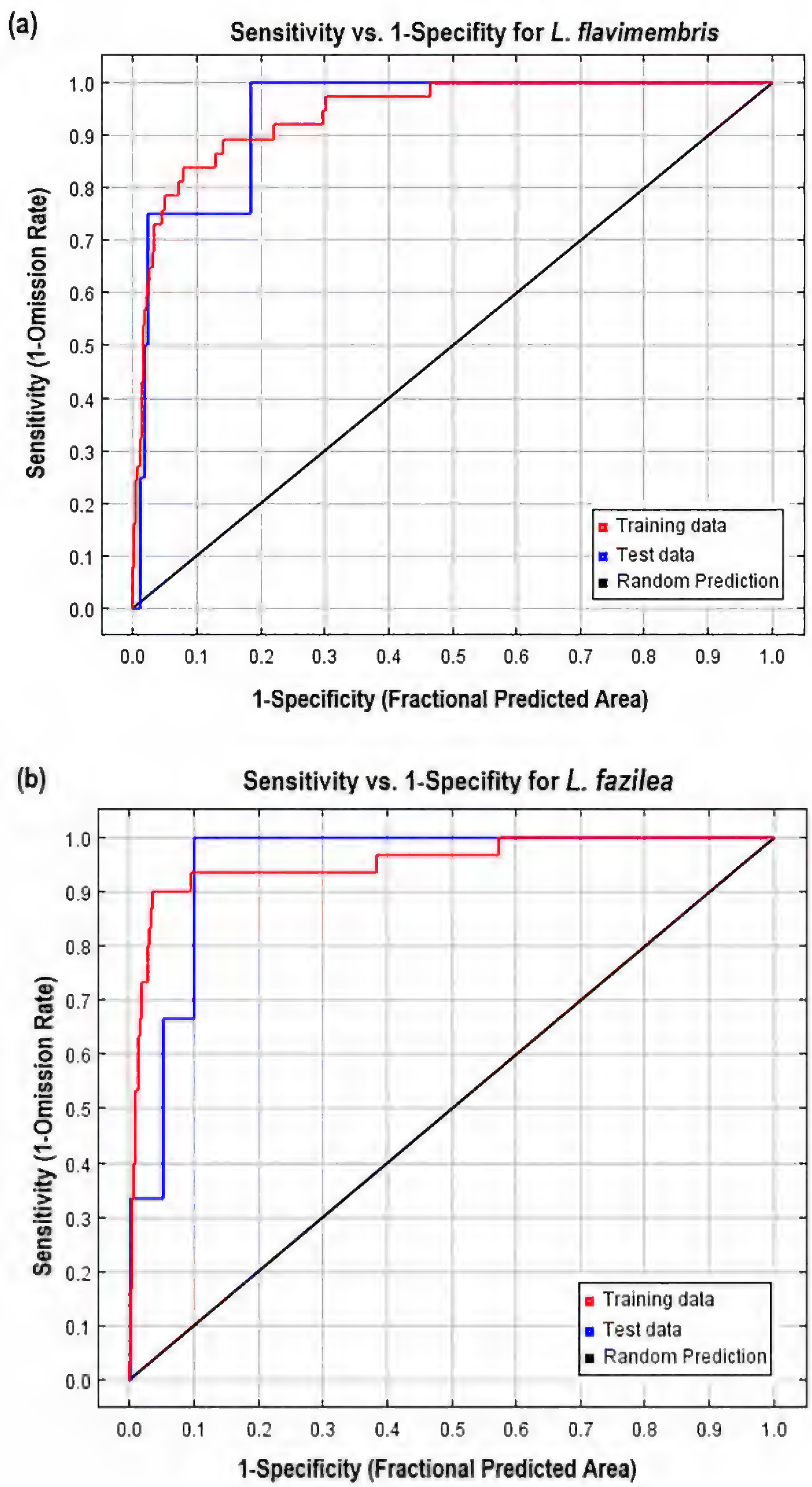


Fig. 2. The receiver operating characteristic (ROC) curves for *L. flavimembris* **(a)** and *L. fazilae* **(b)**.

variables which limit the geographical distribution ranges included three variables for *L. flavimembris* and four for *L. fazilae* (Fig. 3). The percentages of contribution to the model and occurrence intervals of these environmental variables are given in Table 1. The variables with the highest contributions to the model were: Bedrock, Precipitation of Coldest Quarter, and Normalized Difference Vegetation Index for *L. flavimembris* (Table 1 and Fig. 4a); and Bedrock, Precipitation of Coldest Quarter, Temperature Seasonality, and Precipitation Seasonality for *L. fazilae* (Table 1 and Fig. 4b). Combined, these variables explained 86.3% and 99.1% of the variation in the two species distributions, respectively.

The habitat suitability models showed the potential distributions of the two species, and the predicted models confirmed the mostly known geographical ranges of both of them (Fig. 5). The area of high predicted probability of occurrence for *L. flavimembris* was concentrated around the Kötekli, Ula, Milas, and Marmaris districts (Fig. 5a). In particular, the southwestern part of Marmaris district is

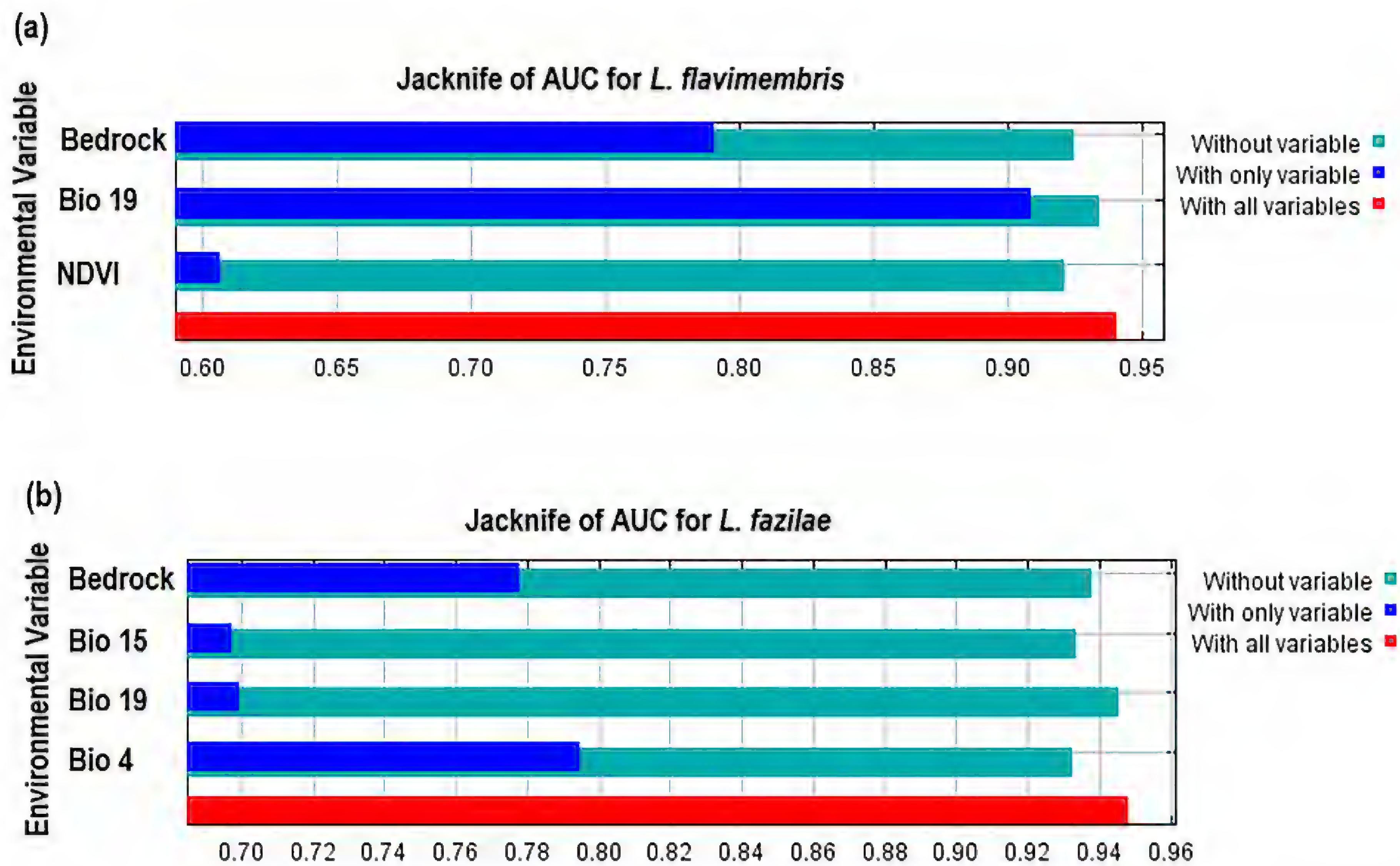


Fig. 3. Results of the Jackknife test for evaluating the relative importance of environmental variables for *L. flavimembris* **(a)** and *L. fazilae* **(b)**. See Table 1 for definitions of the environmental variables.

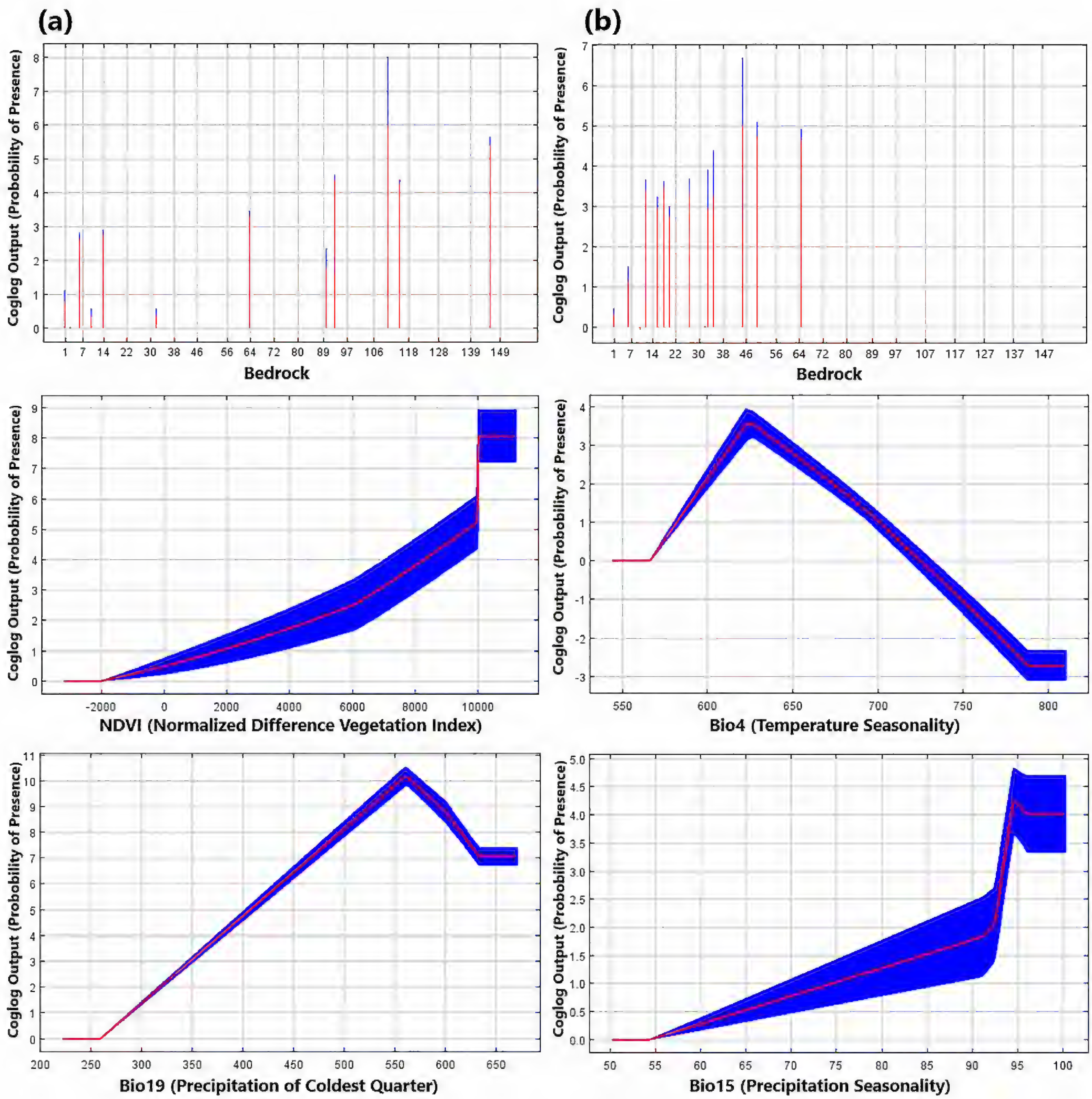
the most intensely occupied area for *L. flavimembris*. In relation to the habitat suitability model of *L. flavimembris*, the field studies revealed two new localities: Kızılköy (36°41'N, 28°06' E; 204 m asl) in the Selimiye district, and İçmeler (36°46'N, 28°12'E; 142 m asl) in the Marmaris district. For *L. fazilae*, the habitat suitability model indicated a high probability of occurrence mostly in known habitats, such as Gökçeovacık (Fethiye), Üzümlü (Fethiye), Dalyan (Ortaca), Kapıkargın (Dalaman), and Sultaniye (Köyceğiz) (Fig. 5b).

Discussion

According to the MaxEnt results, the average contributions (in percentage) of the key environmental variables to the model were determined as: Bedrock (54.2%), Precipitation of Coldest Quarter (41.7%), and NDVI (4.1%) for *L. flavimembris*; and Bedrock (62.3%), Precipitation of Coldest Quarter (25.4%), Temperature Seasonality (8.5%), and Precipitation Seasonality (3.8%) for *L. fazilae*.

The most important factor limiting the distributions of both *L. flavimembris* and *L. fazilae* is bedrock type rather than any of the climatic conditions. Species that prefer specific bedrock types need corridors made up of suitable bedrock to expand their distributions (Sinervo et al. 2017). It is known that salamanders which live in suitable bedrock often hide in the cracks, cavities, and underground of this bedrock under unfavorable climatic conditions (Baran and Atatur 1998). These cracks and holes maintain proper moisture and temperature conditions. The MaxEnt outputs of environmental variables showed that *L. flavimembris* prefers 10 of the 154 bedrock types in the region, while *L. fazilae* prefers nine bedrock types (Fig. 6). While previous studies revealed only limestone (Göçmen and Karış 2017; Veith et al. 2001), this study shows that *L. flavimembris* and *L. fazilae* can be found under different types of stones but their habitats mostly include limestone and cherty limestone.

Amphibians have a high climatic sensitivity due to their ectothermic physiology and their constant need for moisture (Wells 2007). Previous studies have emphasized that humid areas, areas with a dense green cover, an average annual rainfall of 800–1,500 mm, and rocks with moist ground crevices are suitable habitats for Lycian salamanders (Baran and Atatur 1998; Veith et al. 2001). Rödder et al. (2011) investigated the climatic niche similarities between the Lycian salamander species using 19 bioclimatic data sets. That study found that Lycian salamanders (except for *L. helverseni*) preferred similar climatic conditions, and the mean Temperature of Coldest Quarter (variable Bio11) ranged from 6–12.5 °C and Precipitation of Coldest Quarter (Bio19) ranged from 350–620 mm. The species-specific studies have shown that *Pinus brutia*, Mediterranean maquis, green mosses, and limestones are indicators for *L. flavimembris* habitat (Göçmen and Karış 2017), and the air temperature interval of the active season of *L. flavimembris* ranged from 5–21 °C, while monthly average precipitation ranged from



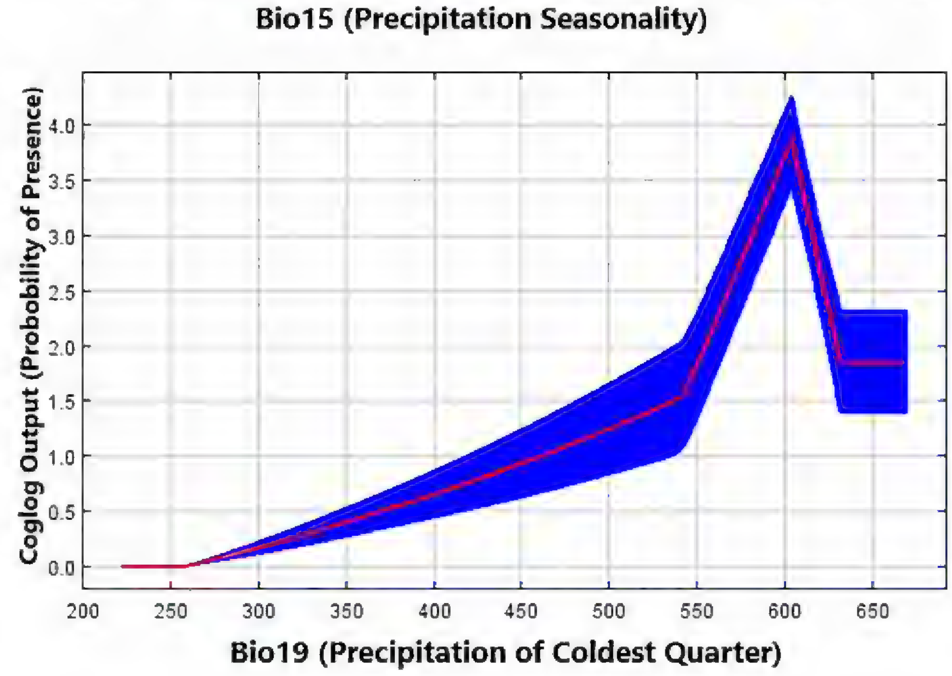


Fig. 4. Variables with the highest contributions to the potential distributions of *L. flavimembris* **(a)** and *L. fazilae* **(b)** according to MaxEnt, with the standard errors in shown blue. In each graph, the y-axis indicates the probability of presence and the x-axis shows the contribution of each variable. See Table 1 for definitions of the environmental variables.

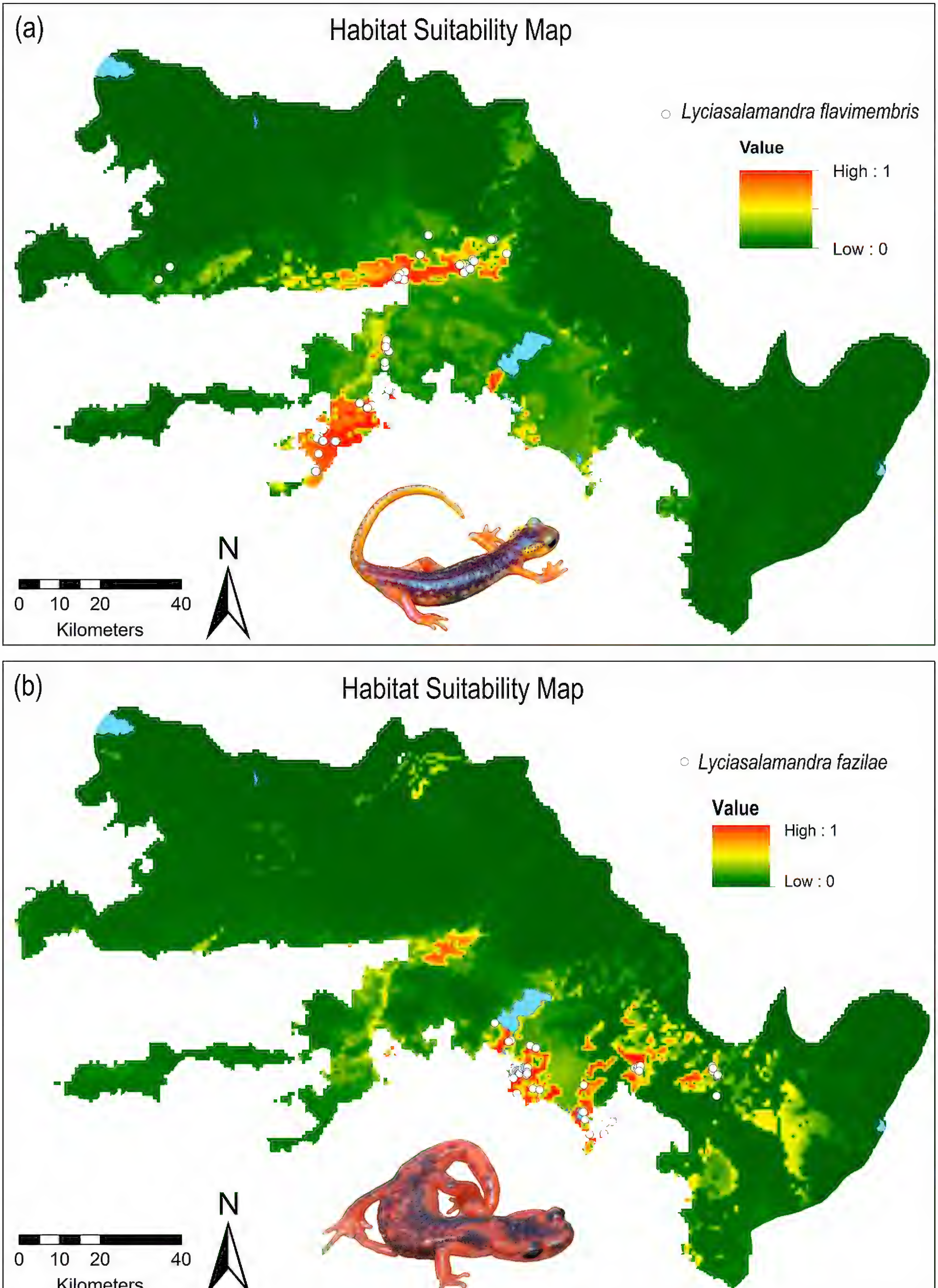


Fig. 5. MaxEnt habitat suitability maps for *L. flavimembris* **(a)** and *L. fazilae* **(b)**.

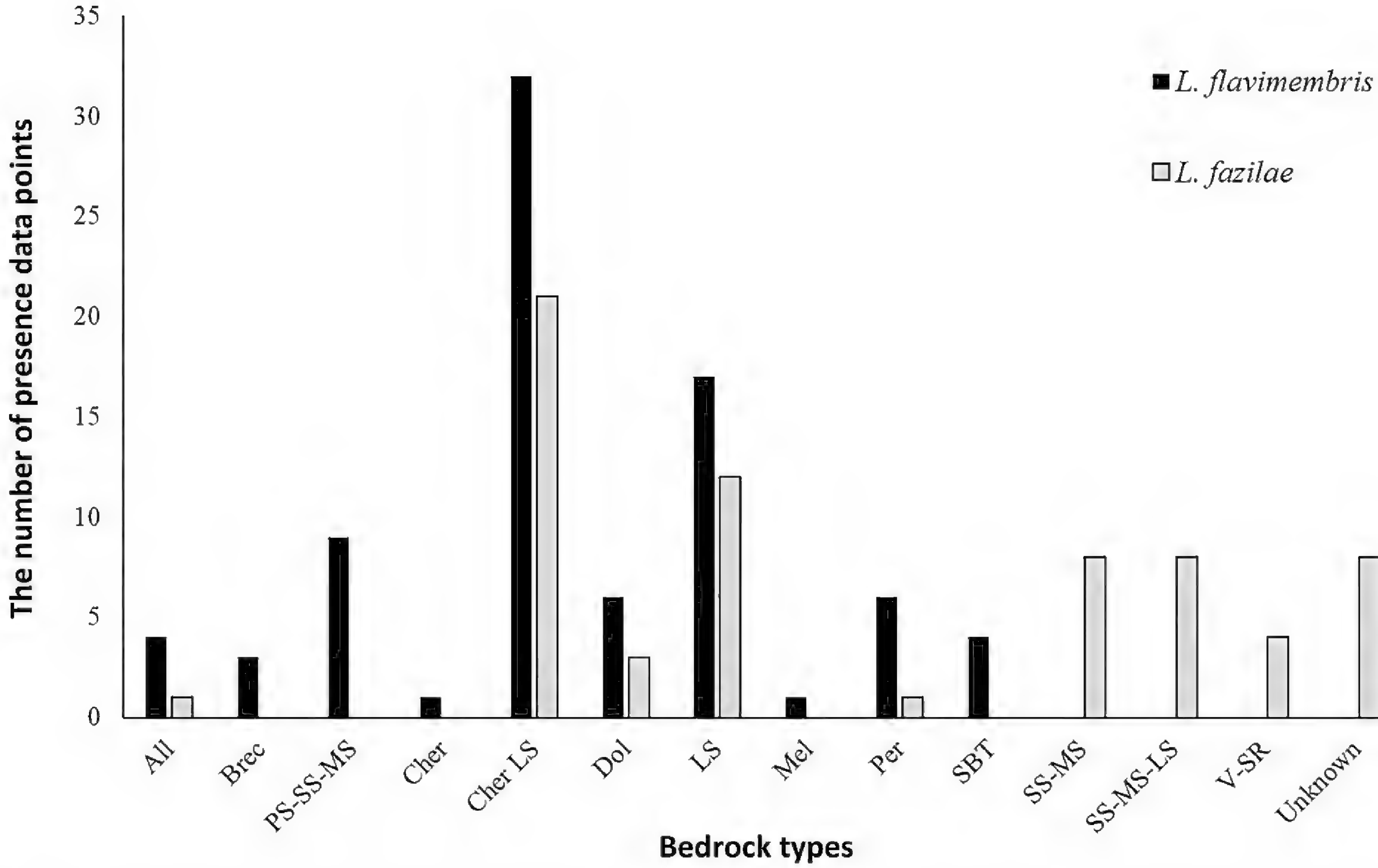


Fig. 6. Frequencies of Bedrock types on the different presence points of *L. flavimembris* and *L. fazilae*. Bedrock type abbreviations: Alluvion [All], Breccias [Brec], Pebble Stone-Sandstone-Mudstone [PS-SS-MS], Chert [Cher], Cherty Limestone [Cher LS], Dolomite [Dol], Limestone [LS], Melange [Mel], Peridotite [Per], Spilite-Basalt-Tuff [SBT], Sandstone-Mudstone [SS-MS], Sandstone-Mudstone-Limestone [SS-MS-LS], Volcanite-Sedimentary Rock [V-SR], and all unknown rock types [Unknown].

57–335 mm (Başkale et al. 2019). On the other hand, Polat and Başkale (2018) stated that the greatest number of individuals of *L. fazilae* was observed at temperatures between 2 and 18 °C (mean 12.99 ± 0.403 °C), and that the active period started with the first autumn rains and a sharp decrease in air temperature (< 20 °C), and ended with higher air temperatures (22 °C and above).

Climatic conditions may also limit the distributions of both species, resulting in narrow distribution areas. Our habitat suitability models show that *L. flavimembris* and *L. fazilae* both have specific demands with respect to precipitation and temperature. Specifically, the Precipitation of Coldest Quarter (Bio19) is 500–650 mm for *L. flavimembris*, while for *L. fazilae* the Precipitation of Coldest Quarter (Bio19; 600 mm), Precipitation Seasonality (Bio15; 100 mm), and Temperature Seasonality (Bio4; 5–6 °C) were found to be important predictors of its distribution. These results show that the current climatic conditions are sufficient for *L. fazilae* and *L. flavimembris* to survive. This supports the MaxEnt ClogLog values for *L. fazilae* and *L. flavimembris* given in Veith et al. (2020), which showed the prevalence of unsuitable current climatic conditions for the survival of many of the Lycian salamanders other than *L. fazilae* and *L. flavimembris*.

In our models, vegetation is another of the environmental factors that determine the distributions of the two salamander species. *Lyciasalamandra flavimembris* was detected in areas with an NDVI of 10,000, indicating green areas with high canopy cover. For *L. fazilae*, the interval of the NDVI value was wider (1,000–10,000), hence its distribution area is characterized by more heterogeneous vegetation, such as pine forests, Mediterranean marquis, and olive tree fields. Our habitat compatibility model obtained with the MaxEnt method is compatible with the known biology of Lycian salamanders (Baran and Atatur 1998; Özeti and Yılmaz 1994; Veith et al. 2001). Another consistency in our results is that the locations with the highest population densities and abundances of *L. flavimembris* and *L. fazilae* shown in Polat and Başkale (2018) and Başkale et al. (2019) are the same as the localities with high suitability values in our habitat suitability map.

Our habitat suitability maps mostly reflect the known localities of both species, but it is important to consider some differences between the predicted model and the known habitats. For *L. flavimembris*, the habitat suitability map shows inhabitable areas to the west. Although the Yalıkavak and Mazı Mountain (Milas) populations (Oğuz et al. 2020) are located in this area, the potential distribution is extended even to the Bodrum district. This suggests that there are either important barriers to the species' dispersion, or it has simply not yet been recorded from these areas. Moreover, the model predicted suitable habitats for *L. fazilae* within the distribution area of *L. flavimembris* (see also Veith et al. 2020). This situation arises from the fact that both species prefer similar environmental variables such as Precipitation of Coldest Quarter and Bedrock. On the other hand, Veith et al. (2020) showed a strong degree of isolation among *Lyciasalamandra* populations, including phyloclades of *L. fazilae*, and two subspecies of *L. fazilae* are recognized: *L. f. fazilae* and *L. f. ulfetae* (Göçmen et al. 2018). However, Veith et al. (2020) claimed that the *L. fazilae* phyloclade diversity is higher than that reflected by current taxonomy, with five phyloclades forming three well-supported phylogenetic clusters: (faz-I + faz-II), faz-III, and (faz-IV + faz-V). The vertical extension of the Taurus Mountains between the Göcek and Dalaman districts constitutes the first (faz-I + faz-II) and the second (faz-III) phylogenetic clusters. However, the third cluster (Ülemez population and Sultaniye population) is geographically isolated by the Köyceğiz Lake and Dalyan Canal in the east, and the Ulemez Mountain and the extensions of Taurus Mountains in the west and northwest (see Figs. 1 and 5b).

In conclusion, potential distribution maps of *L. flavimembris* and *L. fazilae* were created based on bioclimatic data and some environmental variables. These maps indicated that the current climatic conditions of the regions where both species live are suitable for the survival of the species. In addition, some populations of *L. flavimembris* (i.e., Yaylasöğüt and Arıcılar) and *L. fazilae* (i.e., Üzümlü and Gökçeovacık) were located far from the Mediterranean coast, indicating that these species can tolerate more diverse climatic conditions. This study is an important step for the conservation of endangered species within and outside existing protected areas, and may help alleviate the population decline of both species.

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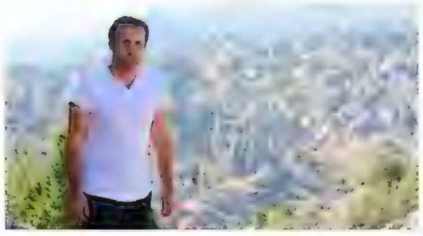

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